6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide (CO_2) flux caused by (1) changes in forest carbon stocks, (2) changes in non-forest soil carbon stocks, and (3) changes in non-forest carbon stocks in landfills. Six components of forest carbon stocks are analyzed: trees, understory, forest floor, forest soil, wood products, and landfilled wood. The estimated CO_2 flux from each of these forest components is based on carbon stock estimates developed by the U.S. Forest Service, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in non-forest soil carbon stocks include mineral and organic soil carbon stock changes due to agricultural land use and land management, and emissions of CO_2 due to the application of crushed limestone and dolomite to agricultural soils. The methods in the *Revised 1996 IPCC Guidelines* were used to estimate all three components of changes in non-forest soil carbon stocks. Changes in non-forest carbon stocks in landfills are estimated for yard trimmings disposed in landfills using EPA's method of analyzing life cycle GHG emissions and sinks associated with solid waste management (EPA 1998).

Unlike the assessments in other chapters, which are based on annual activity data, the flux estimates in this chapter, with the exception of emissions from liming and carbon storage associated with yard trimmings disposed in landfills, are based on periodic activity data in the form of forest and soil surveys. Carbon dioxide fluxes from forest carbon stocks and from non-forest mineral and organic soils are calculated on an average annual basis over five- or ten-year periods. The resulting annual averages are applied to years between surveys. As a result of this data structure, estimated CO_2 fluxes are constant over multi-year intervals. In addition, because the most recent national forest survey was completed for the year 1992, the estimates of the CO_2 flux from forest carbon stocks are based in part on modeled projections of stock estimates for the year 2000.[1]

The previous U.S. Inventory included only a preliminary assessment of the net CO_2 flux from two non-forest soil components: use and management of organic soils and liming of agricultural soils. In the current Inventory, revised estimates of flux from organic soils—based on revised activity data—updated flux estimates for liming of agricultural soils—based on updated activity data—and flux estimates for non-forest mineral soils are included. However, due to the lack of a national soil survey more recent than 1992, carbon flux estimates for non-forest mineral and organic soils were not calculated for the 1993 through 1998 period. Therefore, the non-forest soil carbon flux estimates are not included in the total fluxes reported for this chapter.

[1] The national forest survey for 1997 is expected to be completed this year. This survey will be used to develop revised forest carbon flux estimates, which will be presented in the 1990-1999 version of the U.S. Inventory.

Estimates of total annual net CO_2 flux from land-use change and forestry decline from 316 to 211 MMTCE (1,160,000 to 773,000 Gg) net sequestration between 1990 and 1998 (Table 6-1 and Table 6-2). The decrease in annual net CO_2 sequestration is due to a maturation and slowed expansion of the U.S. forest cover and a gradual decrease in the rate of yard trimmings disposed in landfills; the abrupt shift between 1992 and 1993 is a result of the use of methodologies that incorporate periodic activity data and decadal, rather than annual, stock estimates.

Changes in Forest Carbon Stocks

Globally, the most important human activity that affects forest carbon fluxes is deforestation, particularly the clearing of tropical forests for agricultural use. Tropical deforestation is estimated to have released nearly 6 billion metric tons of CO_2 per year during the 1980s, or about 23 percent of global CO_2 emissions from anthropogenic activities. Conversely, during this period about 7 percent of global CO_2 emissions were offset by CO_2 uptake due to forest regrowth in the Northern Hemisphere (Houghton et al. 1995).

Table 6-1: Net CO_2 Flux from Land-Use Change and Forestry (MMTCE)*

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Forests	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)
Soil	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)
Harvested Wood	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Wood Products	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Landfilled Wood	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Landfilled Yard Trimmings	(4.9)	(4.8)	(4.7)	(4.2)	(3.7)	(3.3)	(2.7)	(2.6)	(2.3)
Total Net Flux	**(316.4)**	**(316.1)**	**(316.2)**	**(213.3)**	**(212.8)**	**(211.9)**	**(211.3)**	**(211.2)**	**(210.9)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes flux estimates for non-forest soils due to incomplete flux estimates for organic and mineral soils for the 1990 through 1998 period.

Table 6-2: Net CO_2 Flux from Land-Use Change and Forestry (Gg)*

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Forests	**(1,005,400)**	**(1,005,400)**	**(1,005,400)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**
Trees	(350,500)	(350,500)	(350,500)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)
Understory	(8,800)	(8,800)	(8,800)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)
Forest Floor	(76,300)	(76,300)	(76,300)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)
Soil	(569,100)	(569,100)	(569,100)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)
Harvested Wood	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**
Wood Products	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)
Landfilled Wood	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)
Landfilled Yard Trimmings	(17,800)	(17,500)	(17,100)	(15,300)	(13,600)	(12,000)	(10,000)	(9,400)	(8,300)
Total Net Flux	**(1,160,000)**	**(1,159,700)**	**(1,159,300)**	**(780,000)**	**(778,300)**	**(776,700)**	**(774,700)**	**(774,100)**	**(773,000)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes flux estimates for non-forest soils due to incomplete flux estimates for organic and mineral soils for the 1990 through 1998 period.

In the United States, the amount of forest land has remained fairly constant during the last several decades. The United States covers roughly 2,263 million acres, of which 33 percent (737 million acres) is forest land (Powell et al. 1993). The amount of forest land declined by approximately 5.2 million acres between 1977 and 1987 (USFS 1990, Waddell et al. 1989), and increased by about 5.3 million acres between 1987 and 1992 (Powell et al. 1993). These changes represent average fluctuations of only about 0.1 percent per year. Other major land-use categories in the United States include range and pasture lands (29 percent), cropland (17 percent), urban areas (3 percent), and other lands (18 percent) (Daugherty 1995).

Given the low rate of change in U.S. forest land area, the major influences on the current net carbon flux from forest land are management activities and ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density of the forest, thereby increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils.

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- Trees (i.e., living trees, standing dead trees, roots, stems, branches, and foliage)
- Understory vegetation (i.e., shrubs and bushes)
- The forest floor (i.e., woody debris, tree litter, and humus)
- Soil

As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, and replanting), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage of carbon in living biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the forest carbon pools over time.

The net change in forest carbon, however, may not be equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere.[2] Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 if the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested for energy use, combustion results in an immediate release of carbon. Conversely, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If wood products are disposed of in landfills, the carbon contained in the wood may be released years or decades later, or may even be stored permanently in the landfill.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in an annual net uptake (i.e., sequestration) of carbon. Also, due to improvements in U.S. agricultural productivity, the rate of forest land clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested. The impacts of these land-use changes are still affecting carbon fluxes from forests in the East. In addition to land-use changes in the early part of this century, in recent

[2] For this reason, the term "apparent flux" is used in this chapter.

decades carbon fluxes from Eastern forests were affected by a trend toward managed growth on private land, resulting in a near doubling of the biomass density in eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on reforesting previously harvested lands, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net carbon fluxes. Because most of the timber that is harvested from U.S. forests is used in wood products and much of the discarded wood products are disposed of by landfilling—rather than incineration—significant quantities of this harvested carbon are transferred to long-term storage pools rather than being released to the atmosphere. The size of these long-term carbon storage pools has also increased over the last century.

As shown in Table 6-3 and Table 6-4, U.S. forest components, wood product pools, and landfilled wood were estimated to account for an average annual net sequestration of 311.5 MMTCE (1,142,200 Gg CO_2) from 1990 through 1992, and 208.6 MMTCE (764,700 Gg CO_2) from 1993 through 1998. The net carbon sequestration reported for 1998 represents an offset of about 14 percent of the 1998 CO_2 emissions from fossil fuel com-

Table 6-3: Net CO_2 Flux from U.S. Forests (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Apparent Forest Flux	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)
Forest Soils	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)
Apparent Harvested Wood Flux	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Apparent Wood Product Flux	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Apparent Landfilled Wood Flux	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Total Net Flux	**(311.5)**	**(311.5)**	**(311.5)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**

Note: Parentheses indicate net carbon "sequestration" (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word "apparent" is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 6-4: Net CO_2 Flux from U.S. Forests (Gg)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Apparent Forest Flux	**(1,005,400)**	**(1,005,400)**	**(1,005,400)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**	**(627,900)**
Trees	(350,500)	(350,500)	(350,500)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)	(271,300)
Understory	(8,800)	(8,800)	(8,800)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)	(4,600)
Forest Floor	(76,300)	(76,300)	(76,300)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)	(35,800)
Soil	(569,100)	(569,100)	(569,100)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)	(316,300)
Apparent Harvested Wood Flux	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**	**(136,800)**
Wood Products	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)	(65,500)
Landfilled Wood	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)	(71,200)
Total Net Flux	**(1,142,200)**	**(1,142,200)**	**(1,142,200)**	**(764,700)**	**(764,700)**	**(764,700)**	**(764,700)**	**(764,700)**	**(764,700)**

Note: Parentheses indicate net carbon "sequestration" (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word "apparent" is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

bustion. The average annual net carbon sequestration reported for 1993 through 1998 represents a 33 percent decrease relative to the average annual net carbon sequestration reported for 1990 through 1992. This overall decrease in annual net sequestration is due to changes in the aggregate age structure of U.S. forests caused by the maturation of existing forests and the slowed expansion of Eastern forest cover. The abrupt shift in annual net sequestration from 1992 to 1993 is the result of calculating average annual fluxes using periodic activity data as well as models that estimate and project decadal rather than annual stock estimates.

Methodology

The methodology for estimating annual forest carbon flux in the United States differs from the methodologies employed for other activities because the forest carbon flux estimates were derived from periodic surveys rather than annual activity data. In addition, because the most recent survey was completed for 1992, a combination of survey data and projected data, rather than complete historical data, was used to derive some of the annual flux estimates.

Timber stock data from national forest surveys were used to derive estimates of carbon contained in the four forest ecosystem components (i.e., trees, understory, forest floor, and soil) for the survey years. The apparent annual forest carbon flux for a specific year was estimated as the average annual change in the total forest carbon stocks between the preceding and succeeding forest survey years. The most recent national forest surveys were conducted for the years 1987 and 1992. Therefore, the apparent annual forest carbon flux estimate for the years 1990 through 1992 was calculated from forest carbon stocks derived from the 1987 and 1992 surveys. To estimate the apparent annual forest carbon flux estimate for the years 1993 through 1998, the 1992 forest carbon stocks and forest carbon stocks for 2000, which were derived from a projection of timber stocks, were used.[3]

Carbon stocks contained in the wood product and landfilled wood pools were estimated for 1990 using historical forest harvest data, and were estimated for 2000 using projections of forest harvest. Therefore, apparent annual wood product and landfilled wood fluxes for the years 1990 through 1998 were calculated from a 1990 historical estimate and a 2000 projection.[4]

The total annual net carbon flux from forests was obtained by summing the apparent carbon fluxes associated with changes in forest stocks, wood product pools, and landfilled wood pools.

The inventory methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing estimates of net carbon flux from Land-Use Change and Forestry: (1) using average annual statistics on land-use change and forest management activities, and applying carbon density and flux rate data to these activity estimates to derive total flux values; or (2) using carbon stock estimates derived from periodic inventories of forest stocks, and measuring net changes in carbon stocks over time. The latter approach was employed because the United States conducts periodic surveys of national forest stocks. In addition, the IPCC identifies two approaches to accounting for carbon emissions from harvested wood: (1) assuming that all of the harvested wood replaces wood products that decay in the inventory year so that the amount of carbon in annual harvests equals annual emissions from harvests; or (2) accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion). The latter approach was applied for this inventory using estimates of carbon stored in wood products and landfilled wood.[5] Although there are large uncertainties associated with the data used to develop the flux estimates presented here, the use of direct measurements from forest surveys and associated estimates of product and landfilled wood pools is likely

[3] Once the 1997 national forest survey is released, new annual estimates of forest carbon flux will be developed. These new estimates will be reported in the 1990-1999 U.S. Inventory.

[4] These values will also be revised once the 1997 national forest survey is released.

[5] This calculation does not account for carbon stored in imported wood products. It does include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

to result in more accurate flux estimates than the alternative IPCC methodology.

Data Sources

The estimates of forest, product, and landfill carbon stocks used in this inventory to derive forest carbon fluxes were obtained from Birdsey and Heath (1995), Heath et al. (1996), and Heath (1997). The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 1987 and 1992 was estimated using timber volume data collected by the U.S. Forest Service (USFS) for those years (Waddell et al. 1989; Powell et al. 1993). The timber volume data include timber stocks on forest land classified as timberland, reserved forest land, or other forest land[6] in the contiguous United States, but do not include stocks on forest land in Alaska, Hawaii, U.S. territories, or trees on non-forest land (e.g., urban trees).[7] The timber volume data include estimates by tree species, size class, and other categories.

The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 2000 was estimated by Birdsey and Heath (1995) using the FORCARB forest carbon model (Plantinga and Birdsey 1993) linked to the TAMM/ATLAS forest sector model (Adams and Haynes 1980; Alig 1985; Haynes and Adams 1985; Mills and Kincaid 1992). The forest stock projections for 2000, therefore, are based on multiple variables, including projections of prices, consumption, and production of timber and wood products; and projections of forest area, forest inventory volume, growth, and removals.

The amount of carbon in aboveground and below ground tree biomass in forests was calculated by multiplying timber volumes by conversion factors derived from studies in the United States (Cost et al. 1990, Koch 1989). Carbon stocks in the forest floor and understory vegetation were estimated based on simple models (Vogt et al. 1986) and review of numerous intensive ecosystem studies (Birdsey 1992). Soil carbon stocks were calculated using a model similar to Burke et al. (1989) based on data from Post et al. (1982).

Carbon stocks in wood products in use and in wood stored in landfills were estimated by applying the HARVCARB model (Row and Phelps 1991) to historical harvest data from the USFS (Powell et al. 1993) and harvest projections for 2000 (Adams and Haynes 1980; Mills and Kincaid 1992). The HARVCARB model allocates harvested carbon to disposition categories (i.e., products, landfills, energy use, and emissions), and tracks the accumulation of carbon in different disposition categories over time.

Table 6-5 presents the carbon stock estimates for forests—including trees, understory, forest floor, and forest soil—wood products, and landfilled wood used in this inventory. The increase in all of these stocks over time indicates that, during the examined periods, forests, forest product pools, and landfilled wood all accumulated carbon (i.e., carbon sequestration by forests was greater than carbon removed in wood harvests and released through decay; and carbon accumulation in product pools and landfills was greater than carbon emissions from these pools by decay and burning).

Uncertainty

There are considerable uncertainties associated with the estimates of the net carbon flux from U.S. forests. The first source of uncertainty stems from the underlying forest survey data. These surveys are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. Therefore, the actual timber volumes contained in forests are represented by average values that are subject to sampling and estimation errors. In addition, the forest survey data that are currently available exclude timber stocks on forest land in Alaska, Hawaii, U.S. territories, and trees

[6] Forest land in the United States includes all land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. In 1992, there were about 490 million acres of Timberlands, which represented 66 percent of all forest lands (Powell et al. 1993). Forest land classified as Timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 34 percent of forest land is classified as Productive Reserved Forest Land, which is withdrawn from timber use by statute or regulation, or Other Forest Land, which includes unreserved and reserved unproductive forest land.

[7] Although forest carbon stocks in Alaska and Hawaii are large compared to the U.S. total, net carbon fluxes from forest stocks in Alaska and Hawaii are believed to be minor. Net carbon fluxes from urban tree growth are also believed to be minor.

Table 6-5: U.S. Forest Carbon Stock Estimates (Gg)

Description	1987	1990	1992	2000
Forests	**36,353,000**	**NA**	**37,724,000**	**39,094,000**
Trees	13,009,000	NA	13,487,000	14,079,000
Understory	558,000	NA	570,000	580,000
Forest Floor	2,778,000	NA	2,882,000	2,960,000
Forest Soil	20,009,000	NA	20,785,000	21,475,000
Harvested Wood	**NA**	**3,739,000**	**NA**	**4,112,000**
Wood Products	NA	2,061,000	NA	2,240,000
Landfilled Wood	NA	1,678,000	NA	1,872,000

NA (Not Available)

Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, U.S. territories, or trees on non-forest land (e.g., urban trees); wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Shaded areas indicate values based on projections. All other values are based on historical data. Totals may not sum due to independent rounding.

on non-forest land (e.g., urban trees); however, net carbon fluxes from these stocks are believed to be minor.

The second source of uncertainty results from deriving carbon storage estimates for the forest floor, understory vegetation, and soil from models that are based on data from forest ecosystem studies. In order to extrapolate results of these studies to all forest lands, it was assumed that they adequately describe regional or national averages. This assumption can potentially introduce the following errors: (1) bias from applying data from studies that inadequately represent average forest conditions, (2) modeling errors (e.g., erroneous assumptions), and (3) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). In particular, the impacts of forest management activities, including harvest, on soil carbon are not well understood. Moore et al. (1981) found that harvest may lead to a 20 percent loss of soil carbon, while little or no net change in soil carbon following harvest was reported in another study (Johnson 1992). Since forest soils contain over 50 percent of the total stored forest carbon in the United States, this difference can have a large impact on flux estimates.

The third source of uncertainty results from the use of projections of forest carbon stocks for the year 2000 (Birdsey and Heath 1995) to estimate annual net carbon sequestration from 1993 to 1998. These projections are the product of two linked models (i.e., FORCARB and TAMM/ATLAS) that integrate multiple uncertain variables related to future forest growth and economic forecasts. Because these models project decadal rather than annual carbon fluxes, estimates of annual net carbon sequestration from 1993 to 1998 are calculated as *average* annual estimates based on projected long-term changes in U.S. forest stocks.

The fourth source of uncertainty results from incomplete accounting of wood products. Because the wood product stocks were estimated using U.S. harvest statistics, these stocks include exports, even if the logs were processed in other countries, and exclude imports. Haynes (1990) estimates that imported timber accounts for about 12 percent of the timber consumed in the United States, and that exports of roundwood and primary products account for about 5 percent of harvested timber.

Changes in Non-Forest Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of photosynthetically fixed carbon (i.e., organic matter such as decayed detritus and roots) and loss of carbon through decomposition. The quantity and quality of organic matter inputs, and the rate of decomposition, are determined by the combined interaction of climate, soil properties, and land-use. Agricultural practices and other land-use activities, such as clearing, drainage, tillage, planting, crop residue management, fertilization, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net flux of carbon to or from soils. In addition, the application of carbonate minerals to soils through liming operations results in emissions of CO_2. The IPCC methodology for changes in non-forest soil carbon stocks (IPCC/UNEP/OECD/IEA 1997) is divided into three categories of land-use/land-management activities: (1) agricultural land-use and land management activities on mineral soils, especially land-use change activities; (2) agricultural land-use and land management activities on organic soils, especially cultivation and conversion to pasture and forest; and (3) liming of soils. Organic soils and mineral soils are treated separately because each responds differently to land-use practices.

Organic soils contain extremely deep and rich layers of organic matter. When these soils are cultivated, tilling or mixing of the soil aerates the soil, thereby accelerating the rate of decomposition and CO_2 generation. Because of the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time. Conversion of organic soils to agricultural uses typically involves drainage as well, which also causes soil carbon oxidation. When organic soils are disturbed, through cultivation and/or drainage, the rate at which organic matter decomposes, and therefore the rate at which CO_2 emissions are generated, is determined primarily by climate, the composition (decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for upland crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and/or more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

Mineral soils contain considerably less organic carbon than organic soils. Furthermore, much of the organic carbon is concentrated near the soil surface. When mineral soils undergo conversion from their native state to agricultural use, as much as half of the soil organic carbon can be lost to the atmosphere. The rate and ultimate magnitude of carbon loss will depend on native vegetation, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40-60 percent of the carbon loss occurs within the first 10 years following conversion; after that, carbon stocks continue to drop but at a much slower rate. In temperate regions, carbon loss can continue for several decades. Eventually, the soil will reach a new equilibrium that reflects a balance between carbon accumulation from plant biomass and carbon loss through oxidation. Any changes in land-use or management practices that result in increased biomass production or decreased oxidation (e.g., crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) will result in a net accumulation of soil organic carbon until a new equilibrium is achieved.

Lime in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) is commonly added to agricultural soils to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate of degradation is determined by soil conditions and the type of mineral applied; it can take several years for agriculturally-applied lime to degrade completely.

Of the three activities, use and management of mineral soils was by far the most important in terms of contribution to total flux during the 1990 through 1992 period (see Table 6-6 and Table 6-7). Because the most recent national survey of land-use and management is from 1992, carbon flux estimates for the years 1993 through 1998 for non-forest organic and mineral soils are not included. Annual carbon sequestration on mineral soils for 1990 through 1992 was estimated at 18.2 MMTCE (66,600 Gg CO_2), while annual emissions from organic soils were estimated at 7.4 MMTCE (27,100 Gg CO_2). Between 1990 and 1998, liming accounted for net annual emissions that ranged from 2.1 to 3.0 MMTCE (7,700 to 11,000 Gg CO_2). Total net annual CO_2 flux from all three activities on non-forest soils (use and management of mineral and organic soils, and liming of soils) was negative over the 1990 to 1992 period (i.e., the combined activities resulted in net carbon sequestration each year). While organic soils and liming both accounted for net CO_2 emissions, the sum of emissions from both activities was more than offset by carbon sequestration in mineral soils.

The emission estimates and analysis for this source are restricted to CO_2 fluxes associated with the use and

Table 6-6: Net CO_2 Flux From Non-Forest Soils (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Mineral Soils	(18.2)	(18.2)	(18.2)	NA	NA	NA	NA	NA	NA
Organic Soils	7.4	7.4	7.4	NA	NA	NA	NA	NA	NA
Liming of Soils	2.2	2.8	2.1	2.1	2.3	2.5	2.4	2.4	3.0

Note: Numbers in parentheses indicate net carbon sequestration.
NA: Not available.

Table 6-7: Net CO_2 Flux From Non-Forest Soils (Gg)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Mineral Soils	(66,600)	(66,600)	(66,600)	NA	NA	NA	NA	NA	NA
Organic Soils	27,100	27,100	27,100	NA	NA	NA	NA	NA	NA
Liming of Soils	8,088	10,224	7,687	7,722	8,455	9,191	8,882	8,702	10,943

Note: Numbers in parentheses indicate net carbon sequestration. Totals might not add up due to independent rounding.
NA: Not available.

management of non-forest mineral and organic soils and liming of soils. However, it is important to note that land-use and land-use change activities may also result in fluxes of non-CO_2 greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO), to and from soils. For example, when lands are flooded with freshwater, such as during hydroelectric dam construction, CH_4 is produced and emitted to the atmosphere due to anaerobic decomposition of organic material in the soil and water column. Conversely, when flooded lands, such as lakes and wetlands, are drained, anaerobic decomposition and associated CH_4 emissions will be reduced. Dry soils are a sink of CH_4, so eventually, drainage may result in soils that were once a source of CH_4 becoming a sink of CH_4. However, once the soils become aerobic, oxidation of soil carbon and other organic material will result in elevated emissions of CO_2. Moreover, flooding and drainage may also affect net soil fluxes of N_2O and CO, although these fluxes are highly uncertain. The fluxes of CH_4, and other gases, due to flooding and drainage are not assessed in this inventory due to a lack of activity data on the extent of these practices in the United States as well as scientific uncertainties about the variables that control fluxes.[8]

Methodology and Data Sources

The methodologies used to calculate CO_2 emissions from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except where noted below.

The estimates of annual net CO_2 flux from mineral soils are based on work by Eve et al. (2000). Eve at al. developed total mineral soil carbon stock estimates for 1982 and 1992 by applying the default IPCC carbon stock and carbon adjustment factors to area estimates derived from U.S. databases on climate (Daly et al. 1994, 1998), soil types and land use and management (USDA 1994), and tillage practices (CTIC 1998). These databases were linked to obtain total area for each combined climate/soil/land-use/tillage category in 1982 and 1992. To derive carbon stock estimates for each year, the areas for each combined category were multiplied by the default IPCC values for soil carbon under native vegetation, and base, tillage, and input factors. The base, tillage, and input factors were adjusted to account for use of a ten-year accounting period, rather than the 20-year period used in the *IPCC Guidelines*. The changes in carbon stocks between 1982 and 1992 for all categories

[8] However, methane emissions due to flooding of rice fields are included, as are nitrous oxide emissions from agricultural soils. These are addressed under the Rice Cultivation and Agricultural Soil Management sections, respectively, of the Agriculture chapter.

were then summed, and divided by ten, to obtain an estimate of total average annual change in carbon C stocks (i.e., net flux) for that period. The *1997 National Resources Inventory*, which will be a 1997 update of USDA (1994), had not been completed at the time this version of the U.S. Inventory was compiled. Publication of the *1997 National Resources Inventory* will enable mineral soil carbon stock estimates for 1997 to be developed, which will allow for estimation of annual average mineral soil carbon flux for 1993 through 1998.

The estimates of annual CO_2 emissions from organic soils are also based on Eve et al. (2000). The procedure used is similar to that for mineral soils, except that organic soils under native vegetation were excluded from the database under the assumption that they are not significantly affected by human activity. Following the IPCC methodology, only organic soils under intense management were included, and the default IPCC rates of carbon loss were applied to the total 1982 and 1992 areas for the climate/land-use categories defined in the IPCC Guidelines. The area estimates were derived from the same climatic, soil, and land-use/land management databases that were used in the mineral soil calculations (Daly et al. 1994, 1998; USDA 1994). As with mineral soils, producing estimates for 1993 through 1998 will be possible once the *1997 National Resources Inventory* is published.

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied (see Table 6-8), by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[9] These emission factors are based on the assumption that all of the carbon in these materials evolves as CO_2. The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey's Mineral Resources Program Crushed Stone Reports and Mineral Industry Surveys (USGS 1993; 1995; 1996; 1997a,b; 1998a,b; 1999a,b). To develop these data, the Mineral Resources Program obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, the estimates of total crushed limestone and dolomite production and use are divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production). To estimate the total amounts of crushed limestone and dolomite applied to agricultural soils, it was assumed that the fractions of "unspecified" and "estimated" production that were applied to agricultural soils were equal to the fraction of "specified" production that was applied to agricultural soils. In addition, data were not available in 1990, 1992, and 1998 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate these data, average annual fractions were derived from data in the other years (i.e., 1991, 1993, and 1994 through 1997) and were applied to the total crushed stone production statistics in 1990, 1992, and 1998.

Table 6-8: Quantities of Applied Minerals (Thousand Metric Tons)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Limestone	15,807	19,820	15,024	15,340	16,730	17,913	17,479	16,539	21,337
Dolomite	2,417	3,154	2,297	2,040	2,294	2,747	2,499	2,989	3,262

[9] Note: the default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) is incorrect. The value provided is 0.122 metric ton carbon/metric ton of dolomite; the correct value is 0.130 metric ton carbon/metric ton of dolomite.

Uncertainty

Uncertainties in the flux estimates for mineral and organic soils result from both the activity data and the carbon stock and adjustment factors. Each of the datasets used in deriving the area estimates has a level of uncertainty that is passed on through the analysis, and the aggregation of data over large areas necessitates a certain degree of generalization. The default IPCC values used for estimates of mineral soil carbon stocks under native vegetation, as well as for the base, tillage and input factors, carry with them high degrees of uncertainty, as these values represent broad regional averages based on expert judgment. Moreover, measured carbon loss rates from cultivated organic soils vary by as much as an order of magnitude. In addition, this methodology does not take into account changes in carbon stocks and land-use trends that occurred over longer time periods.

Uncertainties in the estimates of emissions from liming stem primarily from the methodology, rather than the underlying activity data. It can take several years for agriculturally-applied lime to degrade completely. The IPCC method assumes that the amount of mineral applied in any year is equal to the amount that degrades in that year, so annual application rates can be used to derive annual emissions. Further research is required to determine applied limestone degradation rates. Moreover, soil and climatic conditions are not taken into account in the calculations.

Table 6-9: Net CO_2 Flux from Non-Forest Carbon Stocks in Landfills

Year	MMTCE	Gg
1990	(4.9)	(17,800)
1991	(4.8)	(17,500)
1992	(4.7)	(17,100)
1993	(4.2)	(15,300)
1994	(3.7)	(13,600)
1995	(3.3)	(12,000)
1996	(2.7)	(10,000)
1997	(2.6)	(9,400)
1998	(2.3)	(8,300)

Note: Parentheses indicate sequestration.

Changes in Non-Forest Carbon Stocks in Landfills

As is the case with landfilled forest products, carbon contained in landfilled yard trimmings can be stored indefinitely. In the United States, yard trimmings (i.e., grass clippings, leaves, branches) comprise a significant portion of the municipal waste stream. In 1990, the EPA estimated discards of yard trimmings to landfills at over 21 million metric tons. Since then, programs banning or discouraging disposal, coupled with a dramatic rise in the number of composting facilities, have decreased the disposal rate for yard trimmings; the 1998 landfill disposal was about 10 million metric tons. The decrease in the yard trimmings landfill disposal rate has resulted in a decrease in the rate of landfill carbon storage from about 4.9 MMTCE in 1990 to 2.3 MMTCE in 1998 (see Table 6-9).

Yard trimmings comprise grass, leaves, and branches and have long been a significant component of the U.S. waste stream. In 1990, discards (i.e., landfilling plus combustion) of yard trimmings were about 27.9 million metric tons, representing 17.9 percent of U.S. disposal of municipal solid waste (EPA 1999). Unlike most of the rest of the waste stream, yard trimmings disposal has declined consistently in the 1990s—generation has declined at 3.3 percent per year, and recovery (e.g., composting) has increased at an average annual rate of 15 percent. Laws regulating disposal of yard trimmings now affect over 50 percent of the U.S. population, up from 28 percent in 1992 (EPA 1999). By 1997, discards were about 15 million metric tons, representing 10 percent of U.S. municipal waste disposal.

Methodology

The methodology for estimating carbon storage is based on a life cycle analysis of greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). According to this methodology, carbon storage is the product of the mass of yard trimmings disposed, on a wet weight basis and a storage factor. The storage factor is based on a series of experiments designed to evaluate methane generation and residual organic material in landfills under average conditions

(Barlaz 1997). These experiments analyzed grass, leaves, branches, and other materials, and were designed to promote biodegradation by providing ample moisture and nutrients.

For purposes of this analysis, the composition of yard trimmings was assumed to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches. A different storage factor was used for each component. The weighted average carbon storage factor is 0.19 Gg carbon per Gg of yard trimmings, as shown in Table 6-10. Results, in terms of carbon storage, are also shown.

Data Sources

The yard trimmings discard rate was taken from the EPA report *Characterization of Municipal Solid Waste in the U.S.: 1998 Update* (EPA 1999), which provides estimates for 1990 through 1997 and forecasts for 2000 and 2005. Yard trimmings discards for 1998 were projected using the EPA (1999) forecast of generation and recovery rates (decrease of 6 percent per year, increase of 8 percent per year, respectively) for 1997 through 2000. This report does not subdivide discards of individual materials into volumes landfilled and combusted, although it does provide an estimate of the overall distribution of solid waste between these two management methods (76 percent and 24 percent, respectively) for the waste stream as a whole.[10] Thus, yard trimmings disposal to landfills is the product of the quantity discarded and the proportion of discards managed in landfills (see Table 6-11). The carbon storage factors were obtained from EPA (1998).

Uncertainty

The principal source of uncertainty for the landfill carbon storage estimates stem from an incomplete understanding of the long-term fate of carbon in landfill environments. Although there is ample field evidence that many landfilled organic materials remain virtually intact for long periods, the quantitative basis for predicting long-term storage is based on limited laboratory results under experimental conditions. In reality, there is likely to be considerable heterogeneity in storage rates, based on (1) actual composition of yard trimmings (e.g., oak leaves decompose more slowly than grass clippings) and (2) landfill characteristics (e.g., availability of moisture, nitrogen, phosphorus, etc.). Other sources of uncertainty include the estimates of yard trimmings disposal rates—which are based on extrapolations of waste composition surveys, and the extrapolation of a value for 1998 disposal from estimates for the period from 1990 through 1997.

Table 6-10: Composition of Yard Trimmings (%) in MSW and Carbon Storage Factor (Gg Carbon/Gg Yard Trimmings)

Component	Percent	Storage Factor
Grass	50	0.11
Leaves	25	0.36
Branches	25	0.19
Total/ Weighted Average	**100**	**0.19**

Table 6-11: Yard Trimmings Disposal to Landfills

Year	Metric Tons
1990	21,236,000
1991	20,822,000
1992	20,408,000
1993	18,168,000
1994	16,203,000
1995	14,265,200
1996	11,962,300
1997	11,197,000
1998	9,929,500

[10] Note that this calculation uses a different proportion for combustion than an earlier calculation in the waste combustion section of Chapter 6. The difference arises from different sources of information with different definitions of what is included in the solid waste stream.